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14. ABSTRACT

Developing the ultra-fast (> 100 GHz) near-ballistic uni-traveling carrier photodiode (NBUTC-PD), advanced optical pulse shaper system, and ultrafast TDS system to demonstrate the photonic generation and detection of (near) real-time arbitrary sub-THz waveform with ultra-wide bandwidth and ultra-short transient time.

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Proposal Title:

Photonic Generation and Detection of Arbitrary MMW Waveform for High-Resolution MMW Radar Imaging **(From 2013/03/01 to 2014/03/01)**

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Abstract:

By combing the ultra-fast (> 100 GHz) near-ballistic uni-traveling carrier photodiode (NBUTC-PD) and advanced optical pulse shaper system, we demonstrate the photonic generation and detection of (near) real-time arbitrary waveform at W-band with ultra-high time-bandwidth product. By use of such setup, remote-ranging (5 meters) at W-band with fine resolution (< 5 mm), has also been successfully achieved.

Introduction:

The real time millimeter-wave (MMW) arbitrary waveform generation remains a challenge in now day due to the limited bandwidth of electrical arbitrary waveform generator (AWG). Radio Frequency (RF) photonics has long been considered an attractive methodology for generating wideband electrical waveforms in the microwave and millimeter wave frequency range. Recently, among the various RF photonic generation methods that have been proposed, those that are based on optical pulse shaping and frequency-to-time mapping have seen considerable interest due to their ability to generate arbitrary waveforms [1-5]. Arbitrary waveforms have considerable potential for impact to electronic warfare applications; however, due to the speed of conventional photodetectors, these techniques have been primarily restricted to below 50 GHz. In addition, the frequency resolution and dynamic response (frequency sweeping time) of optical pulse shaper based approach are still hard to be competed with the existed electrical solution in microwave frequency regime. On the other hand, in order to convert the optical MMW envelope into high-power MMW signal for practical application, a photodiode (PD) has not only ultrafast optical-to-electrical (O-E) bandwidth (> 100 GHz) but also high saturation power (~mW level) are highly desired. In this project [6, 7], we have utilized a high power near-ballistic uni-traveling-carrier (NB-UTC) photodiode [8,9] to expand on previous baseband RF-AWG work and demonstrated generation, transmission, and ranging in the W-band (75-110 GHz). There are three major breakthroughs in such project. The first is that we have demonstrated the photonic generation of truly continuous MMW chirped pulse waveform at W-band with record-high time bandwidth product. Furthermore, the repetition rate and pulse-width can be manipulated to fit the radar application. Second is that we have verified that our photonic generation scheme can offer a much lower (~15 dB lower) phase noise than that of state-of-the-art electrical AWG with up-converted frequency to W-band. Third is that by use of these generated waveforms, proto-type photonic radar system with ultra-fine range resolution (~3.9 mm) has been demonstrated. These results would be of vital importance for next generation high-resolution MMW radar system..

Results:

Figure 1 shows the conceptual diagram of our system setup. By use of the home-made photonic-transmitter-mixer chip [8] and the advanced shaper system, complex MMW waveform at W-band has been successfully demonstrated. Figure 2 shows the generated chirp pulse waveform with extremely-high time-bandwidth product at W-band by use of our setup [6,7].

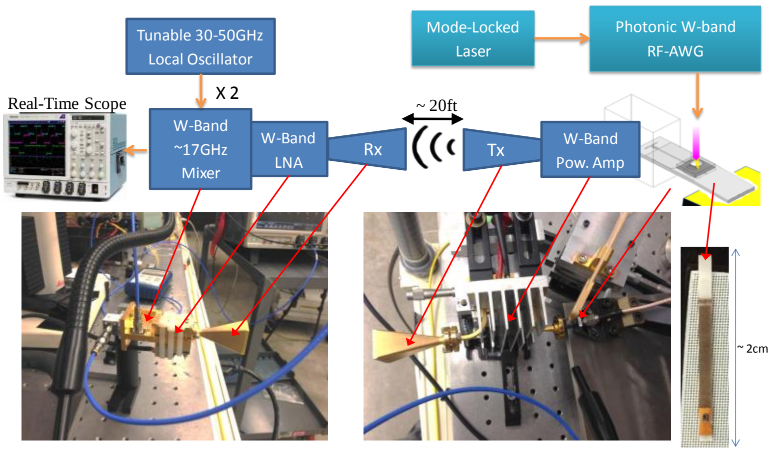

Fig. 1. The system setup for our MMW arbitrary waveform generation at W-band.

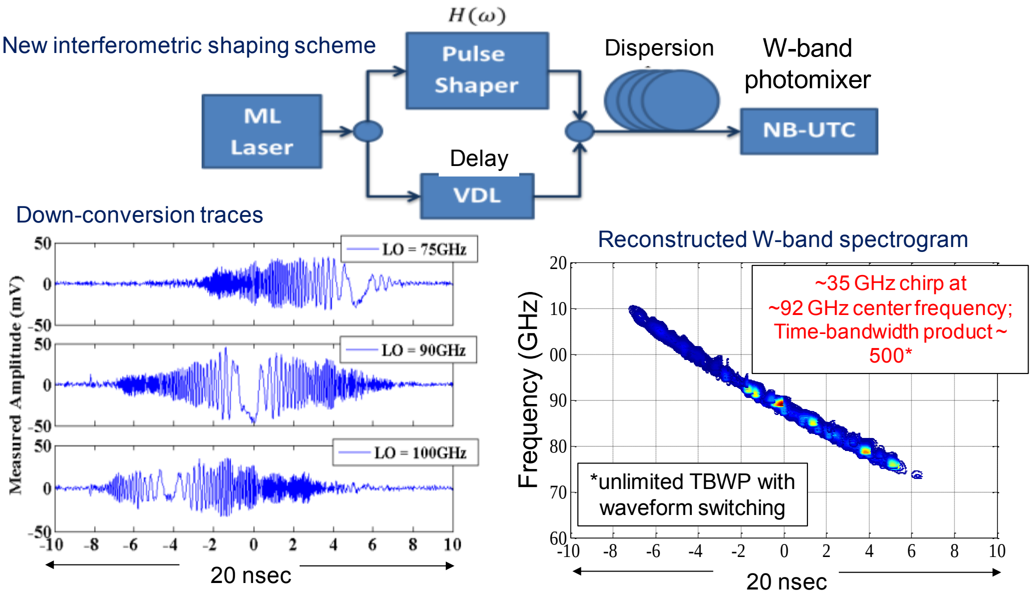

Fig. 2. The waveform of generated MMW chirp pulse

From the application point of view, strong repeatability and low jitter are major requirements for the generated waveforms. For example, in pulse compression radar, repeatable generation of low-jitter sensing waveforms is a vital factor in achieving high-performance systems while maintaining low cost and complexity in the transceiver circuitry. To justify this repeatability, we recorded a measurement of 4000 consecutive 2ns-aperture down-chirp waveforms. The first down-chirp waveform is chosen as a reference and we utilize cross-correlations (without any offline phase alignment) with the reference to evaluate the similarity between these different down-chirp waveforms. These cross-correlations are overlaid in the same temporal frame in Fig. 3 in blue. For comparison the autocorrelation of the reference is also computed and plotted in the same frame in red. Clearly, all 4000 correlations match each other very closely, providing compelling evidence of highly repeatable waveform generation. Next, in order to evaluate the phase-noise characteristic of our RF-AWG apparatus, we program a single frequency tone at 80 GHz using the interferometric RF-AWG setup, as shown in Figure 2, and after down-conversion with a 78 GHz LO, perform single-sideband (SSB) phase-noise analysis using the phase-noise utility of our spectrum analyzer. The blue curve in Fig. 4 plots the SSB phase-noise of the generated (and down-converted) 80 GHz tone in the W-band. This phase-noise curve includes both the noise from the 80 GHz tone itself and the phase-noise of the LO signal used in the down-conversion stage. The phase-noise of the 78 GHz LO signal is also plotted in the same figure in green. Specifically, as we observe from comparing these two curves, at frequency deviations above 10 kHz, phase-noise is dominated by the LO signal, and not that of the W-band tone generated through our RF-AWG scheme. We also measure the phase-noise of a 5 GHz continuous RF signal, generated with an electronic arbitrary waveform generator (Tektronix AWG 7000A, 9.6 GHz analog bandwidth at 6 dB), and project its phase-noise - assuming ideal frequency multiplication - to 80 GHz (plotted in red). Here we assume that the phase-noise scales as the multiplication factor squared, which gives a 24 dB increase for ideal ×16 multiplication. Note that this scaling factor is only a lower bound and does not account for any additional degradation that may occur in practical electronic or photonic-assisted frequency multiplication. Furthermore, this scaling does not include any of the phase-noise from the down-conversion measurement to which the experimental optical phase curve is subject. Figure 4 clearly shows that our scheme's phase-noise for W-band generation substantially outperforms that projected for a frequency multiplied commercial electronic arbitrary waveform generator at all offset frequencies measured. According to the measurement, the phase-noise advantage of our scheme is as high as 35 dB (at ~3.5 kHz offset).

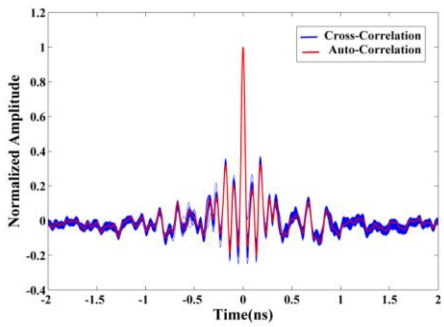

Fig. 3. Cross-correlations between a reference chirped waveform and 4000 consecutive linear down-chirp waveforms (in blue) and autocorrelation of the reference down-chirp waveform (in red).

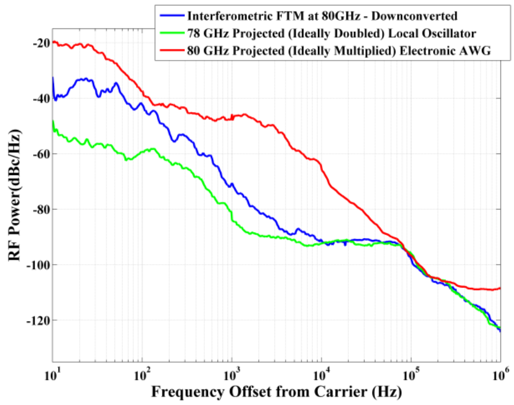

Fig. 4. Phase-noise comparison of 80 GHz continuous waveform (generated using photonic-assisted interferometric RF-AWG and down-converted with an LO at 2×39 GHz = 78 GHz), expected (projected) 78 GHz local oscillator phase-noise, and a 5 GHz signal from an electrical arbitrary waveform generator ideally multiplied to 80 GHz.

By use of the generated chirped pulse waveform and concept of switching pulse, remote ranging (~ 5 meter) with ultra-fine resolution (less than ~3.9 mm) at W-band has been demonstrated. Figure 5 shows the system setup and measurement results.

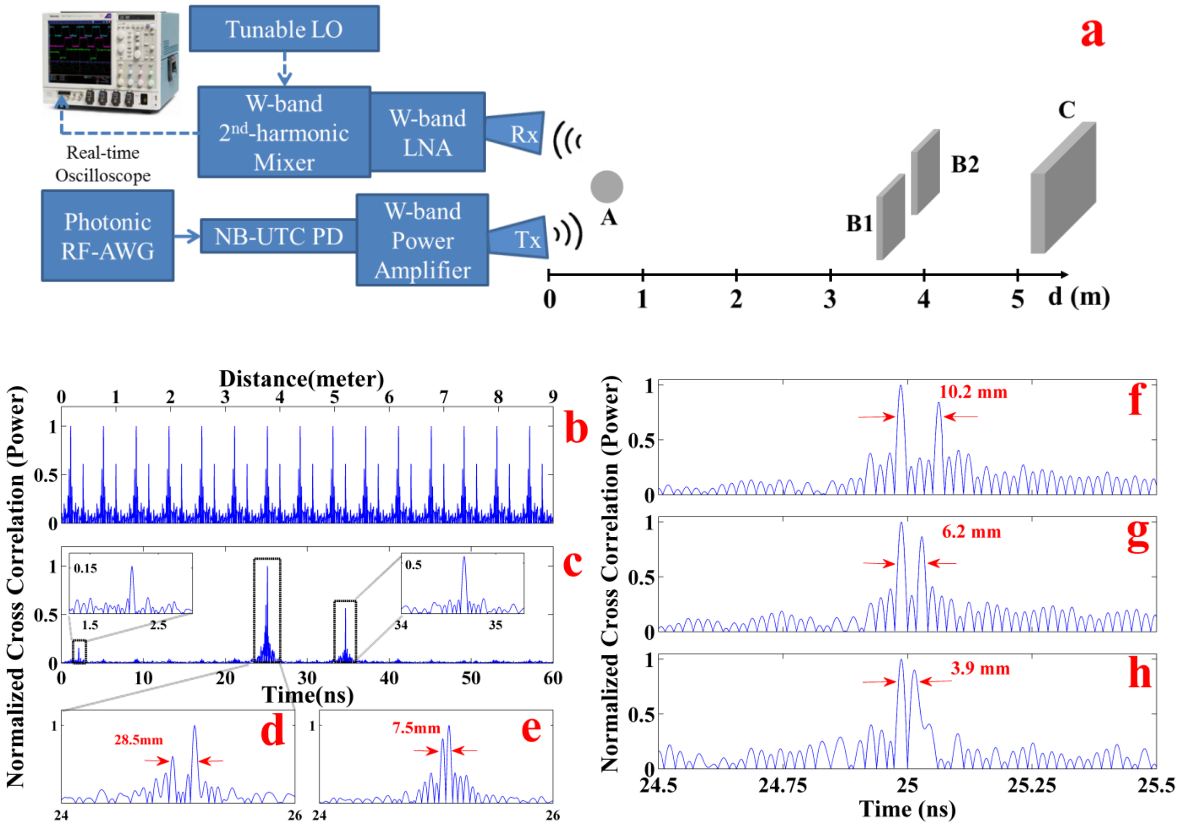

Fig. 5. Ultra-high resolution W-band ranging experiments. (a) Setup schematic. Ball A with radius 4 cm. Flat sheets B1 and B2 are 10×10 cm. Flat sheet C is 10×15 cm. (b) Long range W-band ranging with unmodulated sensing waveforms. (c) Long range W-band ranging with length-15 PN-modulated sensing waveforms. (d) Magnified view from 24-26 ns of (c). (e) Achieved finest range resolution (single measurement). (f), (g), (h) Ultrafine W-band ranging experimental results with ~ 10mm, ~ 6mm and ~ 4mm target separation (multiple measurements).

Conclusion:

With the help of a high-performance NBUTC-PD based photonic mixer module, we report photonic-assisted generation of RF arbitrary waveforms in the 70-110 GHz W-band frequency region. These waveforms can span the full W-band with the maximum TBP supported by the optical pulse shaper, highly-attractive phase-noise characteristics, arbitrarily-long repetition period, and high stability. With appropriate photodetector and antenna technologies, it should be possible to extend these techniques to even higher frequency regions. As an application example, we utilize the

tailored W-band signals in ranging experiments, demonstrating both ultrafine depth resolution (down to 3.9 mm) and unambiguous detection over a range of more than 5 meters. These results can be significantly enhanced by increasing the bandwidth of the measurement block and lengthening the PN modulation sequence. Our work features reconfigurable low-jitter waveform generation with instantaneous RF frequency unprecedented in this frequency range and offers potential for new horizons in high resolution ranging, high-speed wireless communication, electromagnetic imaging and tomography, and high-speed spectroscopy.

Publications

Journal

1. Jhih-Min Wun, Chia-Chien Wei, Jyehong Chen, Chee Seong Goh, S. Y. Set, and Jin-Wei Shi, "Photonic chirped radio-frequency generator with ultra-fast sweeping rate and ultra-wide sweeping range," *Optics Express,* vol. 21, No. 9, pp. 11475-11481, May, 2013.
2. Tzu-Fang Tseng, Jhih-Min Wun, Wei Chen, Sui-Wei Peng, Jin-Wei Shi, and Chi-Kuang Sun,"High-depth-resolution 3-dimensional radar-imaging system based on a few-cycle W-band photonic millimeter-wave pulse generator," *Optics Express,* vol. 21, No. 12, pp. 14109-14119, June, 2013.
3. Jhih-Min Wun, Hao-Yun Liu, Cheng-Hung Lai, Yi-Shiun Chen, S.-D. Yang, Ci-Ling Pan, J. E. Bowers, C.-B. Huang, and Jin-Wei Shi, "Photonic High-Power 160 GHz Signal Generation by using Ultra-Fast Photodiode and a High-Repetition-Rate Femtosecond Optical Pulse Train Generator," to be published in *IEEE J. of Sel. Topics in Quantum Electronics*, vol. 20, Nov.,/Dec., 2014.
4. Yihan Li, Amir Rashidinejad, Jhih-Min Wun, Daniel E. Leaird, Jin-Wei Shi,[2] Andrew M. Weiner, "Photonic Generation of W-band Arbitrary Waveforms with High Time-Bandwidth Products Enabling 3.9mm Range Resolution," submitted to *Optica*

Conference

1. Jhih-Min Wun, Yi-Shiun Chen, Cheng-Hung Lai, Hao-Yun Liu, C.-B. Huang, Ci-Ling Pan, and Jin-Wei Shi, "Strong Enhancement in Saturation Power of Sub-THz Photodiode by Using Photonic Millimeter-Wave Femtosecond Pulse Generator," *Proc. OFC 2014, San Francisco,* CA, USA, March, 2014, pp. Tu2A.5
2. A. Rashidinejad, Yihan Li, Jhih-Min Wun, Daniel Leaird, Jin-Wei Shi, and Andrew Weiner, "Photonic Generation and Wireless Transmission of W-band Arbitrary Waveforms with High Time-Bandwidth Products," in Technical Digest of Conference on Lasers and Electro-Optics, paper SM1G.1, San Jose, CA, USA, June 2014.
3. Yihan Li, A. Rashidinejad, Jhih-Min Wun, Daniel Leaird, Jin-Wei Shi, Andrew Weiner, "High Resolution Unambiguous Ranging Based on W-band Photonic RF-Arbitrary Waveform Generation," in Technical Digest of Conference on Lasers and Electro-Optics, paper SM1G.2, San Jose, CA, USA, June 2014.

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[5] Y. Li, A. Dezfooliyan, and A. M. Weiner, "Photonic Synthesis of Spread Spectrum Radio Frequency Waveforms with Arbitrarily Long Time Apertures," *IEEE Journal of Lightwave Technology,* vol. 32, pp. 3580-3587, Oct., 2014.

[6] Yihan Li, A. Rashidinejad, Jhih-Min Wun, Daniel Leaird, Jin-Wei Shi, Andrew Weiner, "High Resolution Unambiguous Ranging Based on W-band Photonic RF-Arbitrary Waveform Generation," in Technical Digest of Conference on Lasers and Electro-Optics, paper SM1G.2, San Jose, CA, USA, June, 2014.

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[8] N. W. Chen, J. W. Shi, H. J. Tsai, J. M. Wun, F. M. Kuo, J. Hesler, *et al.,* "Design and demonstration of ultra-fast W-band photonic transmitter-mixer and detectors for 25 Gbits/sec error-free wireless linking," *Optics Express,* vol. 20, pp. 21223-21234, Sep 10 2012.

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